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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

MANEUVERING SIMULATION OF TWO SHIPS PASSING HEAD TO HEAD IN A CANAL

JOHN O'DEA AND STEVEN FISHER

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SHIP PERFORMANCE DEPARTMENT REPORT

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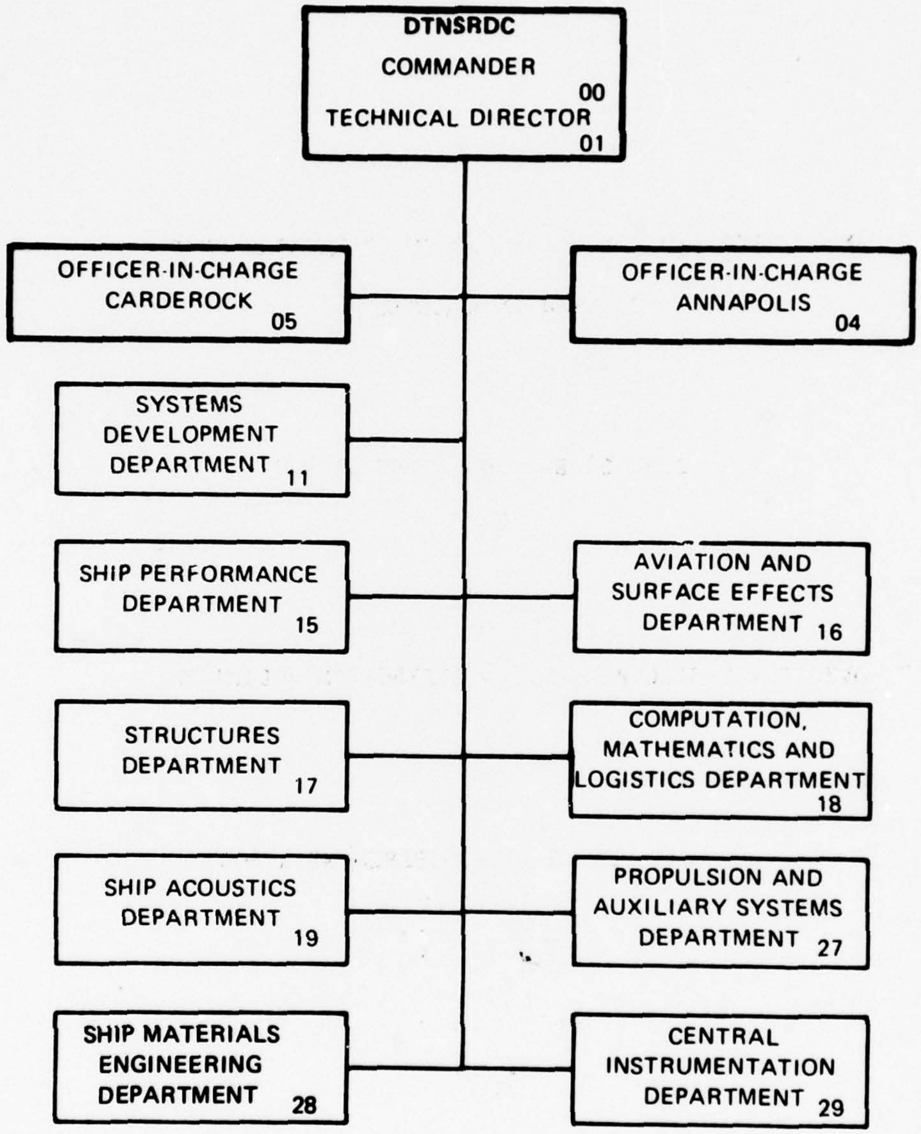

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A series of experiments were run in the 140 foot model basin at the David W. Taylor Naval Ship R&D Center (DTNSRDC) to determine the loads induced on one ship when passed by another ship in a shallow canal. Two 3.84 m LWL ship models were used in the experiments in a 3.05 m wide by .25 m deep canal. Model force and moment loading data and the results from a maneuvering simulation show that two way traffic with large ships in the Gaillard Cut of the Panama Canal may be feasible. The acceleration and deceleration of a ship crossing Miraflores Lake are also discussed.

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TABLE OF CONTENTS

	page
LIST OF FIGURES	iv
LIST OF TABLES	v
NOMENCLATURE	vi
ABSTRACT	1
INTRODUCTION	2
MANEUVERING DYNAMICS IN A CANAL	2
EXPERIMENTAL ARRANGEMENT	5
DESCRIPTION OF EXPERIMENTS	6
SIMULATIONS OF PASSING MANEUVERS	7
ACCELERATION AND DECELERATION IN MIRAFLORES LAKE	9
DISCUSSION	10
CONCLUSIONS	13
ACKNOWLEDGEMENTS	14
REFERENCES	15

LIST OF FIGURES

		page
1 -	Coordinate System on Models	16
2 -	Experimental Setup in the 140-foot Model Basin	17
3 -	Models Bow to Bow During Passing Maneuver	18
4 -	Models Midship to Midship During Passing Maneuver	19
5 -	Models Stern to Stern During Passing Maneuver	20
6 -	Strut Bracing Arrangement on the Carriage Model	21
7 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 7.5 knots, h/d = 1.2, $\bar{\eta}_s$ = 15.24 m	22
8 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 7.5 knots, h/d - 1.2, $\bar{\eta}_s$ = 30.48 m	23
9 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 7.5 knots, h/d - 1.5, $\bar{\eta}_s$ = 15.24 m	24
10 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 7.5 knots, h/d = 1.5, $\bar{\eta}_s$ = 30.48 m	25
11 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 6 knots, h/d - 1.2, $\bar{\eta}_s$ = 15.24 m	26
12 -	Forces and Moments Due to Two Ships Passing Head to Head in a Shallow Channel (Model Scale Data) with U_s = 9 knots, h/d - 1.2, $\bar{\eta}_s$ = 15.24 m	27
13 -	Simulated Trajectory for U_s = 7.5 knots, h/d = 1.2, $\bar{\eta}_s$ = 15.24 m	28
14 -	Simulated Trajectory for U_s = 7.5 knots, h/d = 1.2, $\bar{\eta}_s$ = 30.48 m	29
15 -	Simulated Trajectory for U_s = 7.5 knots, h/d = 1.5, $\bar{\eta}_s$ = 15.24 m	30

page

16 - Simulated Trajectory for U_s = 7.5 knots, h/d = 1.5, $\bar{\eta}_s$ = 30.48 m 31

17 - Simulated Trajectory for U_s = 6 knots, h/d = 1.2, $\bar{\eta}_s$ = 15.24 m 32

18 - Simulated Trajectory for U_s = 9 knots, h/d = 1.2, $\bar{\eta}_s$ = 15.24 m 33

19 - Time Histories of Rudder Angle, Heading, and Offset from Centerline of Canal for U_s = 9 knots, h/d = 1.2, $\bar{\eta}_s$ = 15.24 m 34

LIST OF TABLES

1 - Maximum Values of Lateral Offset, Heading and Rudder Angle for Simulated Passing Maneuvers 35

NOMENCLATURE

B	ship beam
d	ship draft
h	canal depth
I_{zz}	ship yaw inertia
k	rudder gain constant
L	ship length
m	ship mass
N	yaw moment
N_v	derivative of yaw moment with respect to sway velocity
$N_{\dot{v}}$	derivative of yaw moment with respect to sway acceleration
N_r	derivative of yaw moment with respect to yaw velocity
$N_{\dot{r}}$	derivative of yaw moment with respect to yaw acceleration
N_δ	derivative of yaw moment with respect to rudder angle
N_η	derivative of yaw moment with respect to offset from centerline
N_p	yaw moment caused by passing ship
r	yaw velocity
U_m	model velocity
U_s	ship velocity
v	sway velocity
W	canal width
x	axial distance between center of gravity of two ships
X_p	drag change caused by passing ship
Y	sway force

NOMENCLATURE

Y_v	derivative of sway force with respect to sway velocity
$Y_{\dot{v}}$	derivative of sway force with respect to sway acceleration
Y_r	derivative of sway force with respect to yaw velocity
$Y_{\dot{r}}$	derivative of sway force with respect to yaw acceleration
Y_δ	derivative of sway force with respect to rudder angle
Y_η	derivative of sway force with respect to offset from centerline
Y_p	sway force caused by passing ship
δ	rudder angle
η	offset of ship center of gravity from canal centerline
$\overline{\eta}$	lateral spacing between sides of ships while passing
ψ	heading of ship relative to canal axis
λ	scale ratio

ABSTRACT

A series of experiments were run in the 140 foot model basin at the David W. Taylor Naval Ship R&D Center (DTNSRDC) to determine the loads induced on one ship when passed by another ship in a shallow canal. Two 3.84 m LWL ship models were used in the experiments in a 3.05 m wide by .25 m deep canal. Model force and moment loading data and the results from a maneuvering simulation show that two way traffic with large ships in the Gaillard Cut of the Panama Canal may be feasible. The acceleration and deceleration of a ship crossing Miraflores Lake are also discussed.

INTRODUCTION

A project is being performed by DTNSRDC for the Panama Canal Company involving the measurement of hydrodynamic forces on large ships operating in the confined waters of the canal. This involves two phases: a study of two ships passing head to head in the Gaillard cut, and a study of the acceleration and deceleration of a ship crossing Miraflores Lake.

Currently, small ships are allowed through the Gaillard cut in two lanes of traffic. However, larger ships are allowed through the cut in one lane only, stopping travel in the other direction. This is done as a safety precaution. The objective of the passing study is to provide guidelines for two way traffic with large ships through the Gaillard Cut to decrease the average transit time.

Experiments were conducted in the 140 foot basin at DTNSRDC to determine the forces and moments exerted on one ship when passed by another ship in a shallow canal. Two 3.84 m Mariner ship models were used in the experiments in a 50:1 scale model of a canal with the same dimensions as the Gaillard cut. Speed, clearances between the two models, and draft were varied. Only head to head passing was investigated. The results from the model tests were used in a maneuvering simulation to determine the effects of the forces and moments on the ship's path and heading.

MANEUVERING DYNAMICS IN A CANAL

The primary purpose of this study is to illustrate the lateral plane motions (deviation from initial path and heading) of a ship in

a narrow, shallow canal when it is passed by another ship moving in an opposite direction. The case of a single ship moving in a canal has been studied by Fujino[1], and his mathematical formulation has been adopted for the passing situation.

The linearized equations of motion for sway and yaw may be written as

$$(m-Y_{\dot{v}})\,\dot{v} = Y_v v + (-mU_s + Y_r)r + Y_{\dot{r}}\dot{r} + Y_\delta \delta + Y_\eta \eta + Y_p$$

$$(I_{zz} - N_{\dot{r}})\dot{r} = N_v v + N_r r + N_{\dot{v}}\dot{v} + N_\delta \delta + N_\eta \eta + N_p \tag{1}$$

where m and I_{zz} are the ship mass and yaw inertia, v and r are sway and yaw velocity, δ is rudder angle and η is the displacement from the canal centerline. The terms Y_v, Y_r, $Y_{\dot{v}}$, $Y_{\dot{r}}$, Y_δ, $Y_{\dot{\eta}}$, N_v, N_r, $N_{\dot{v}}$, $N_{\dot{r}}$, N_δ, and N_η represent the derivatives of side force and yaw moment with respect to the corresponding variables v, r, δ and η ; and the terms Y_p and N_p represent the force and moment loadings imposed by another passing ship. The coordinate system used is shown in Figure 1. The origin is located at the ship center of gravity, the positive x-axis is along the ship centerline toward the bow, and the positive y-axis direction is to port. Positive moment is defined to be counter-clockwise. These equations for the sway and yaw acceleration may be integrated in a time history simulation to produce velocities, which in turn may be integrated to produce the trajectory of ship motion.

In order to carry out the time history simulation, the values of the various coefficients must be known and suitable initial conditions must be prescribed. The equations of motion, without the terms describing passing loads and displacement from canal centerline, have been used

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*A complete listing of references is given on page 15 .

extensively to simulate the dynamics of a single ship moving in unrestricted waters. There is an extensive data base of coefficients for this situation, including many coefficients representing nonlinear effects not shown in the equations above. For the case of a single ship moving in a canal, the available data is much more limited. Side force and yaw moment coefficients due to offset from a canal centerline have been calculated analytically by Beck[2], with fair agreement with experimental data. The most complete set of data was obtained by Fujino[1], who did experiments on a Mariner hull in shallow water and in a canal. His data has been used for the simulations presented in this report.

Fujino has shown that, because of the asymmetry of flow when a ship moves along a path off the centerline of a canal, there exists a steady, non zero side force and yaw moment on the ship. The side force acts in a direction that tends to attract the hull to the near canal wall, while the moment is in a direction which turns the bow away from the near wall. Thus, in order for a ship to move along an equilibrium path displaced from a canal centerline, these loads must be offset by a combination of rudder action and ship yaw angle (resulting in an angle of attack which develops "lift"). Preliminary simulation runs were made, using Fujino's coefficients, to determine the required amount of rudder offset to maintain a steady initial path at a prescribed distance off the canal centerline.

Data concerning the loads imposed by another passing ship are even more limited than the data concerning a single ship in a canal. The case of a ship passing another stationary ship in shallow water (but without any width restriction) has been studied by Yung[3], but the only

published data for the case of two ships moving in opposite directions was provided by Moody[4]. Moody presented force and moment data obtained experimentally for two ships passing in a canal, but his data covers only two speeds, one value of the lateral separation distance (η), and one water depth to ship draft ratio (h/d). Because of the lack of passing load data, a major portion of this study was devoted to obtaining such data for additional values of the speed, separation and depth to draft ratio parameters.

EXPERIMENTAL ARRANGEMENT

Experiments were run in the 140-foot basin at DTNSRDC to determine the forces and moments exerted on a ship when passing another ship head to head. The scale ratio $\lambda = 50$ was determined by the width of the basin, 3.05 m , representing the 152.4 m width of the Gaillard cut. The models chosen for this experiment were two 3.84 m Mariners, corresponding to two 192 m ships. The Mariners were identical except for a 3 percent bulb on one of the models. The basin was filled to a depth of .25 m, modeling a depth of 12.8 m in the Gaillard cut.

The model on which the forces and moments were measured was mounted to the carriage by two braced struts. Two force blocks were mounted between the bottom of each strut and the model to measure axial and transverse forces. Since the model was solidly attached to the struts, the model could not sink or trim. This model was mounted .625 m off the centerline of the tank.

The other model followed a 12.7 mm steel cable that ran parallel to the centerline of the tank. Guide arms were mounted to the model

to guide the model along the cable while restraining it in sway and yaw. The arms were moved inboard or outboard of the model to change the spacing between it and the model attached to the carriage. This model was free to sink and trim, and is referred to as the free model as opposed to the fixed model that is attached to the carriage.

Two pulleys were mounted at each end of the tank and a 3.2 mm steel cable was run through them. Both ends of the cable were attached to the carriage, making one continuous loop that ran the length of the tank. The free model was attached to this loop of cable to tow it. This arrangement allowed the free model to be towed indirectly by the carriage at the same speed as the carriage model, but in the opposite direction. Microswitches triggered by the carriage moving down the tank were used to record on a strip chart when the models were bow to bow and stern to stern because the towing wire insured that the models would pass at the same spot in the tank for every run. The towing wire also meant that the free model did not have to be powered. This is an improvement over the setup used by Moody, where the free model used only its propeller to drive it. Figure 2 is a sketch of the setup in the 140 foot basin.

DESCRIPTION OF EXPERIMENTS

The passing tests were run with three different clearances between the two models. The changes were made by moving the free model closer to or further away from the fixed model. The spacings that were used corresponded to full scale spacings of 15.24, 30.48 and 45.72 m between the sides of the ships.

Since the depth to draft ratio is important in shallow water, two depth to draft ratios, 1.2 and 1.5, were used. These represent drafts of 10.67 m and 8.53 m respectively. The different ratios were achieved by only changing the draft of the models. The speeds run were 4.5, 6.0, 7.5, and 9.0 knots, full scale. At the larger spacings, 4.5 knots was not run because the forces and moments were masked by the noise in the data.

Drag, speed, side force, and yaw moment about the center of gravity were plotted on a strip chart for each run. If the fixed model was powered, the thrust and rpm were also plotted. Microswitches triggered by the model carriage would trigger a marker on the strip chart to indicate when the models were bow to bow and stern to stern.

Figures 3 through 5 show the models during different phases of the passing maneuver, and Figure 6 shows the strut attachment system. The measured passing loads are shown in Figures 7 through 12.

SIMULATION OF PASSING MANEUVERS

The equations of motion (1) were programmed on a computer such that time histories of the ship motion parameters could be generated for the various loadings obtained from the passing experiments. The side forces from the experiments were scaled in proportion to λ^3 and the yaw moments were scaled in proportion to λ^4. The scale ratio $\lambda = 50$ resulted in a full scale ship length of 192 m LWL in a 152.4 m wide canal. A two second time increment (full scale) was used in all simulations.

Appropriate initial conditions were obtained by running the simulation program with passing loads set to zero and determining the rudder angle

required to maintain the ship at a distance from the canal centerline equal to that used in the model passing experiments (31.24 m). As shown by Fujino[1], a rudder control gain proportional to heading is required to stabilize a Mariner type hull in a canal. Therefore, a rudder control equation combining offset plus heading sensitivity was used in the simulations. The rudder equation adopted was:

$$\delta = \delta_o + k\psi \tag{2}$$

where δ_o is a constant rudder offset, ψ is the ship heading relative to the canal axis, and k is the rudder control gain. A gain of k = 4 was used in all the simulations. It was found that for h/d = 1.5, the appropriate value of δ_o was 4 degrees to starboard, resulting in a 0.5 degree port heading and a steady rudder angle of 6 degrees starboard to maintain an offset of 31.24 m before the passing phase of a simulation. For h/d = 1.2, a value δ_o = 10.2 degrees (starboard) was required, resulting in 0.3 degrees port heading and a steady 11.5 degree starboard rudder to maintain the prescribed offset. These values of control offset were used in all subsequent passing simulations.

The passing simulations were all made using the experimentally determined passing loads over a range of stagger ratios x/L = 3 to -4, corresponding to the maximum length of run obtainable in the model basin. The resulting ship trajectories are shown in Figures 13-18, corresponding to the loading conditions in Figures 7-12. The displacement from the original path is hardly noticeable, with the worst case being at h/d = 1.2, η = 15.24 m and U_s = 9 knots. For this condition, the time histories of lateral displacement (η), heading (ψ) and rudder angle (δ) are shown

in Figure 19. It should be noted that for this case, the lateral displacement is still increasing at the end of the simulation at $x/L = -3.5$ (the limit of the data available in Figure 12), so that it is not known what the maximum displacement would be for this condition. Maximum values of η, ψ and δ for the other simulated conditions are shown in Table 1.

ACCELERATION AND DECELERATION IN MIRAFLORES LAKE

The problem of crossing Miraflores Lake in a minimum amount of time involves consideration of both the axial dynamics of the ship and the lateral plane dynamics during axial acceleration and deceleration. The optimum propulsion control strategy will be a function of ship mass, hull and propeller hydrodynamics (with propeller turning both ahead and astern), and the dynamic properties of the machinery plant. These factors will be different for the various types of ships using the Panama Canal, and in general, detailed information is not available for these factors for all types of ships. It is recommended that such information be obtained in the future for several selected ship classes (such as a "PANAMAX" tanker or a high powered container ship). An axial motion dynamic simulation, similar to the lateral plane simulation described previously, could then be developed and exercised for the selected ship types, to find the minimum passage time strategy.

The lateral plane dynamics (following a desired path and heading) will be strongly affected by the interaction of the propeller with the hull during deceleration. As shown by Crane[5], when the main propulsion engine is either stopped or reversed, the rudder effectiveness is greatly reduced and the ship is essentially out of control during a stopping maneuver.

Control may be recovered by occasional bursts of forward propeller revolutions, but this type of strategy may not be feasible in Miraflores Lake, where permissible head reach is definitely limited. It is likely that the problem of lateral plane control during stopping will be a severe limitation on ship operation, and tugboats probably will be required to assist a large ship whenever the main engine is stopped or reversed. The number or size of tugs required could be determined from additional simulation studies, but again a major problem would be to obtain the various coefficients necessary for the simulation. In the case of stopping maneuvers, these would include coefficients describing propeller-rudder interaction and tugboat effects as well as the restricted water maneuvering coefficients used in the simulations in this report.

DISCUSSION

The forces and moments increased with decreasing h/d and η , and increasing speed, as expected. The maximum positive moment occurred when the models were approximately stern to stern, but there was also a large negative moment (see Figure 1 for definitions and sign conventions) when the models were between bow to bow and midship to midship. The maximum positive side force (attracting the two ships) occurred just after midship to midship. The models showed decreasing drag between x/L = 0 and 1, and increasing drag between x/L = 0 and -1.

After the two models had passed, the side force, drag, and moment oscillated with a period of 4-1/2 to 5 seconds, with the period fairly independent of speed. These oscillations were relatively large. The peaks of the moment oscillations were just slightly lower than the

maximum moment, and the peaks of the side force were 1/3 to 1/2 of the maximum side force. These oscillations died out very slowly.

A check was made to see if the oscillations were due to the natural frequency of the model and strut system. The model was given a large side force excitation, and the response was recorded. The natural frequency turned out to be approximately one second, and the response died out in 2 to 3 seconds. This means that the phenomenon causing the side force, drag and moment oscillations is not due to the strut system.

The phenomenon might be due to the models causing the development of a transverse standing wave in the tank. The standing wave could be excited by the energy in the wakes from the models. This would explain why the oscillations do not occur before the models meet since the models do not enter the regions where the standing wave has developed until after the models have passed. Also, the period of the standing wave would be relatively independent of the model speed. Finally, the standing wave would die out slowly, explaining the slow decay of the oscillations.

Moody[4] noted the same occurrence in his experiments. His period of oscillation would correspond to a period of 4.95 seconds at our model scale.

Figures 7 through 12 are plots of side force, drag and moment versus stagger ratio. Runs of the fixed model by itself were subtracted from the runs of the two models passing to eliminate the noise due to the carriage. That is why the side force, moment, and drag are approximately zero on these plots before the passing occurs.

In general, the loads imposed by a passing ship do not cause unreasonably large displacements of a ship from its original path, for the conditions

simulated in this report. The worst simulated case is that for a 9 knot speed (both ships), passing with a clearance of 15.24 m between them, and and with a canal depth to draft ratio of 1.2. Under these conditions the ship may be displaced from its original path by more than 6 meters .

As shown in Figure 19, the initial passing phase between x/L = 1 (bow to bow) and 0 (midship to midship) is cruical to the subsequent trajectory simulation. In this phase the passing loads initially repel the bow of the ship away from the passing ship. Because the rudder control equation (2) used in the simulations does not anticipate the passing encounter, but rather only reacts to a heading change caused by integrating the response to the loads, the initial change in heading can cause the ship to move off its original path before it is checked by rudder action. Superimposed on this original transient is an oscillatory motion caused by the observed oscillation in the passing loads, possibly caused by a standing wave set up in the canal by the passing ship. This oscillation, while not the dominant response, forms a significant part of the total ship motion.

The range of parameters covered here is still quite limited, and it is not yet possible to determine the limits of safe two way traffic in a canal. There are a number of other parameters which need to be explored. The size and shape of the passing ships will affect their maneuvering coefficients as well as the passing loads, and only two 192 m ships with the proportions of a Mariner hull were considered here. A more reasonable representation of rudder control is required, which should include anticipation of the passing situation (i.e. the human factor involving a pilot) and the limits on rudder rate and maximum deflection which exist on a real ship.

It is possible that the most severe condition for a passing situation would be when the passing occurs in a bend of a canal, and this situation has not been covered in this report. Since the simulated ship trajectory generally tended to deviate away from the passing ship, toward the canal wall, a ship passing another in a bend could be driven into the outside bank of the canal. Another possibility which must be examined in more detail is that, while the center of gravity of a ship may remain close to a desired path during passing, the heading change imposed by the passing loads may cause the bow or stern to swing sufficiently to collide with either the canal bank or the passing ship.

Finally, it should be noted that the simulation model used here was entirely linear, and it is recognized that many of the hydrodynamic loads may be nonlinear functions of velocity, displacement and heading. At present, the data describing the hydrodynamic loads on ships in canals is very limited, and data on nonlinear effects is virtually unavailable.

CONCLUSIONS AND RECOMMENDATIONS

The model experiments and ship motion simulations reported here indicate that it may be feasible to allow two way traffic with large ships in the Gaillard Cut of the Panama Canal. The simulations indicate that for speeds up to 7.5 knots and side-to-side clearances as small as 15.24 m, a 192 m LWL ship will be displaced from its intended track by less than 6 meters.

However, this study should be considered preliminary since it considers only two identical ships passing in a straight portion of the cut, and only linear coefficients are included in the mathematical model. Further

work is needed to expand the data base of coefficients to cover other types of ships in different types of passing situations, with a more realistic simulation model.

The problem of the axial dynamics of a ship crossing Miraflores Lake, has been discussed briefly, and it has been pointed out that a time history simulation analogous to that used for lateral plane (sway and yaw) dynamics would be a useful tool for studying the problem. At present, this approach is also limited by the severe shortage of data suitable for use in such a simulation. It is recommended that such information be obtained in the future for several selected ship classes (such as a "PANAMAX" tanker or a high powered container ship).

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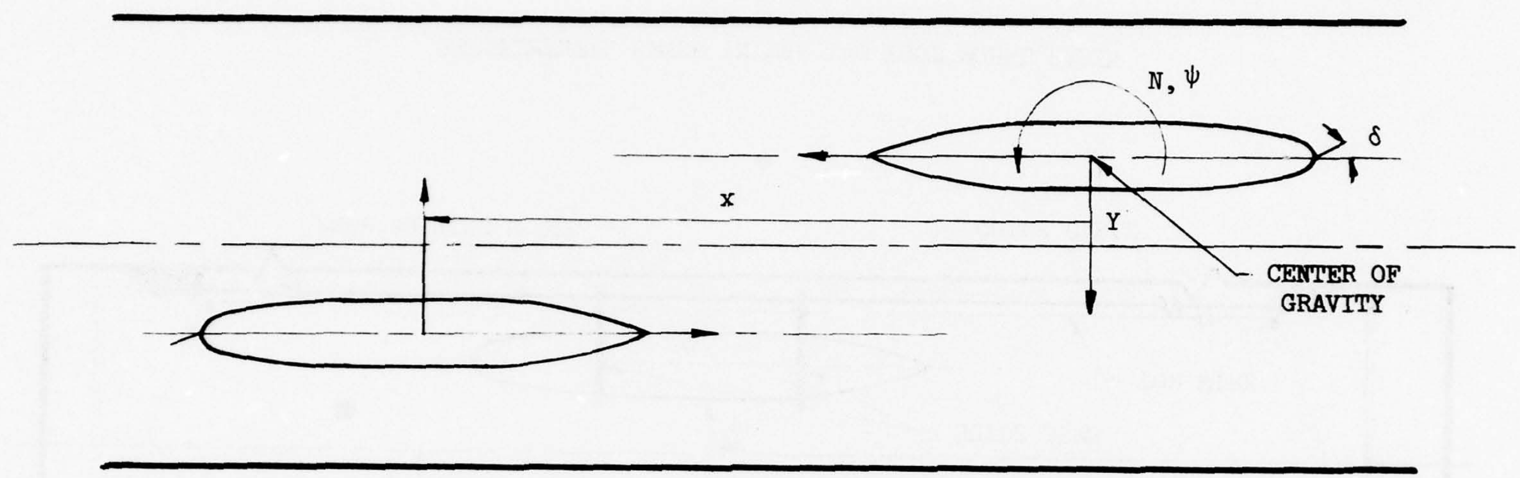
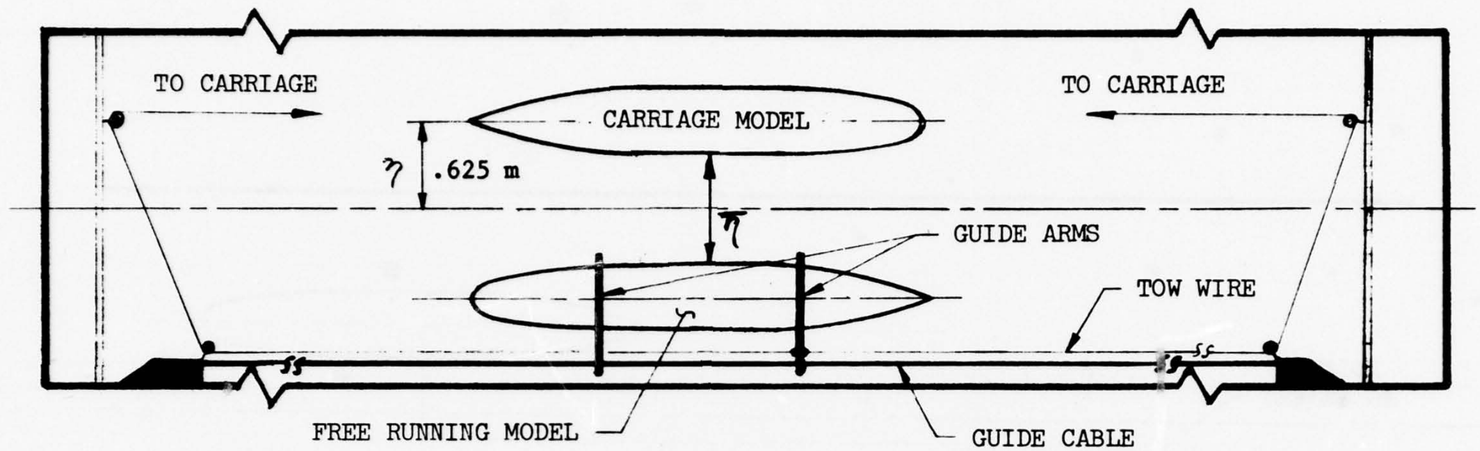


FIGURE 1 COORDINATE SYSTEM ON MODELS



EXPERIMENTAL SETUP IN THE 140 FOOT MODEL BASIN

FIGURE 2

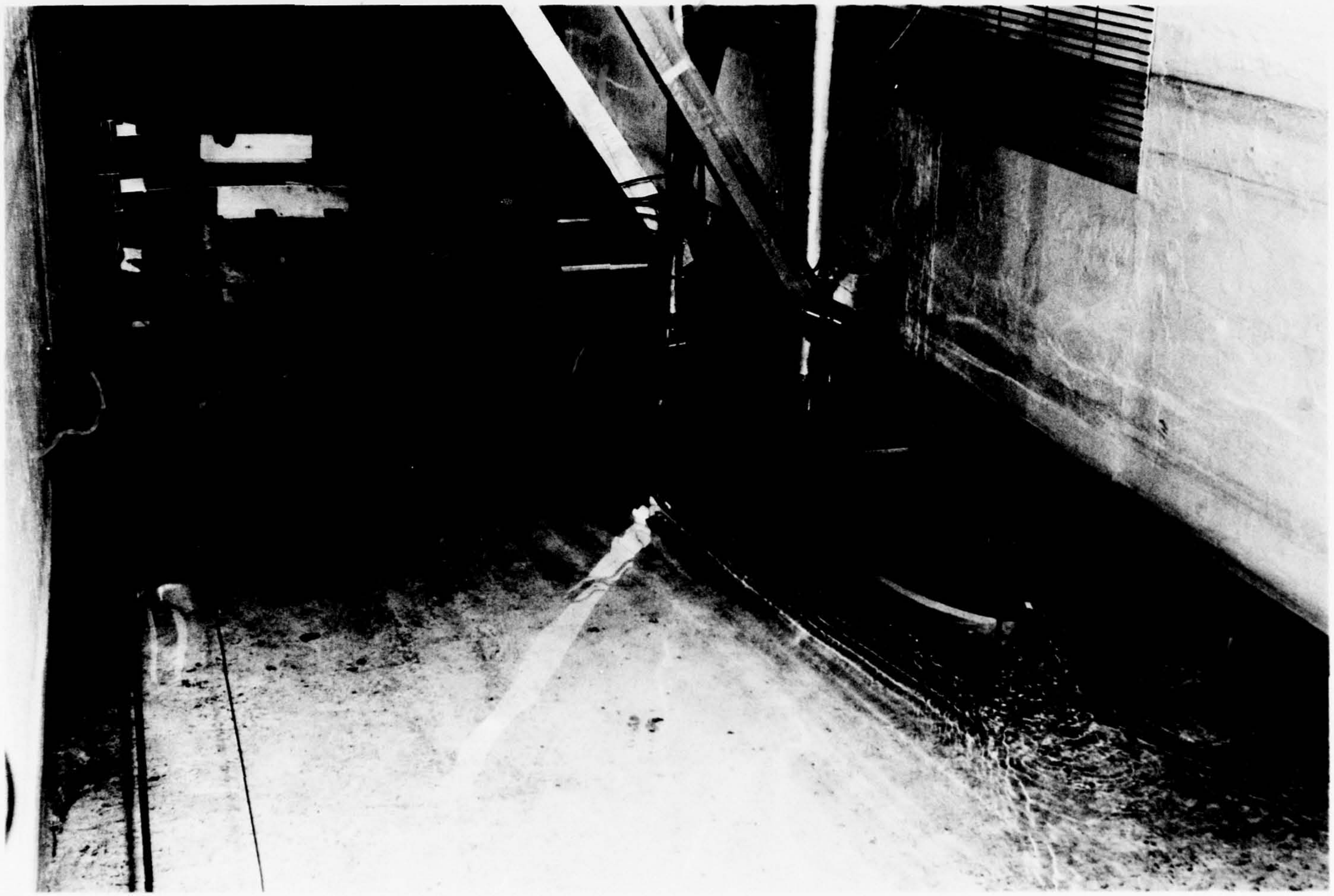


FIGURE 3 MODELS BOW TO BOW DURING PASSING MANEUVER

U_s = 7.5 knots $\ddot{\eta}_s$ = 30.48 m h/d = 1.2

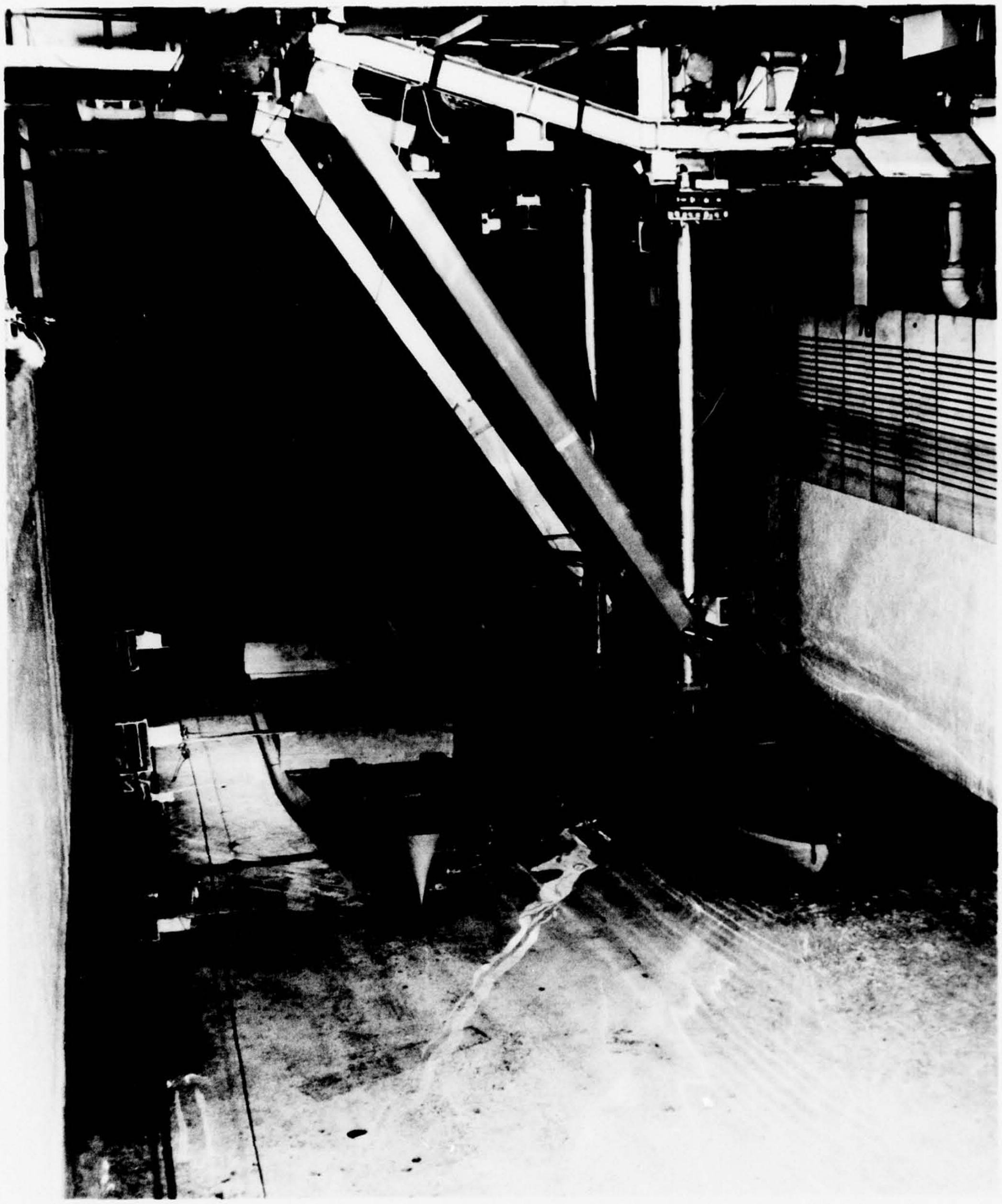


FIGURE 4 MODELS MIDSHIP TO MIDSHIP DURING PASSING MANEUVER

U_s = 7.5 knots $\bar{\eta}_s$ = 30.48 m h/d = 1.2

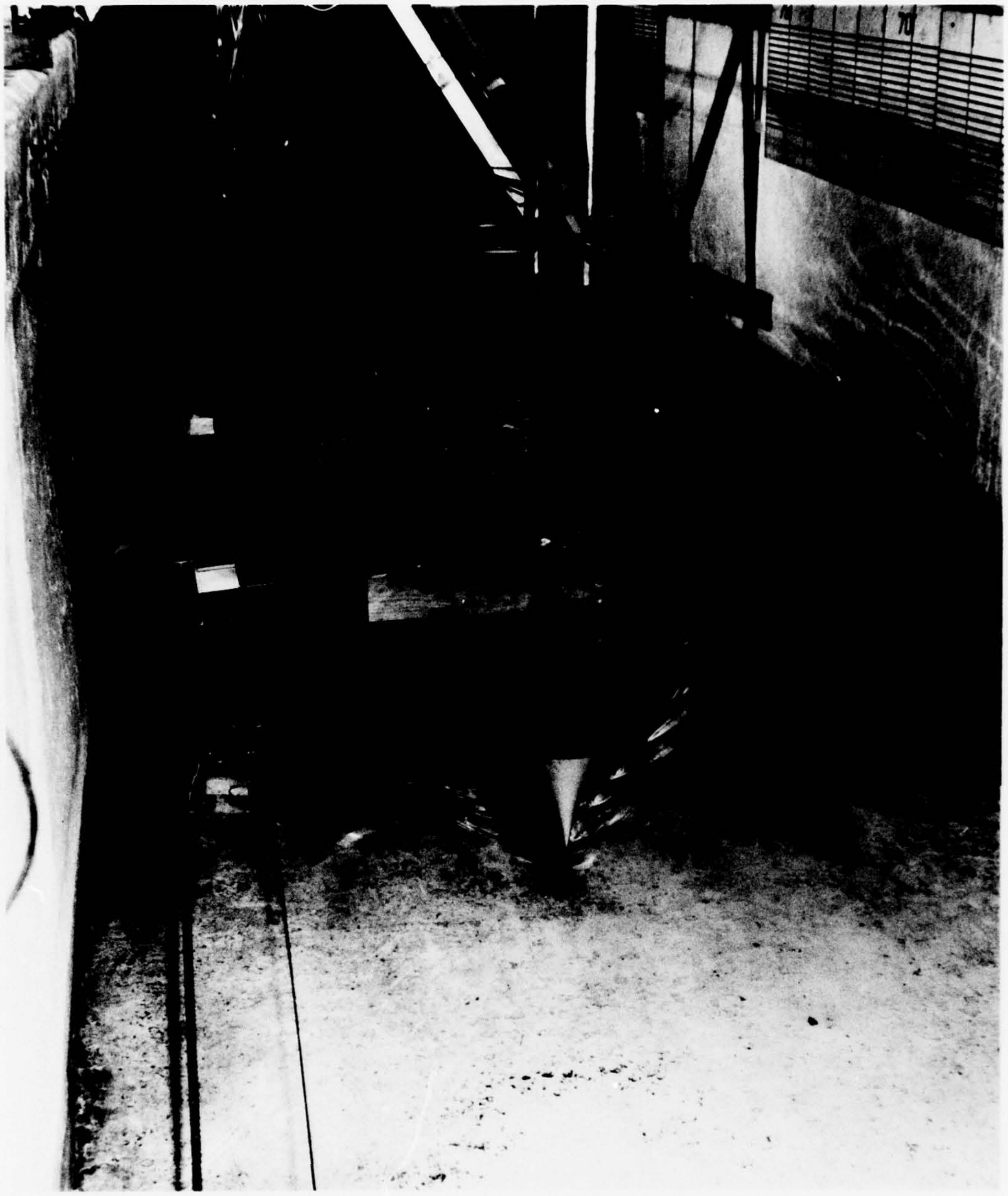


FIGURE 5 MODELS STERN TO STERN DURING PASSING MANEUVER

U_s = 7.5 knots $\bar{\eta}_s$ = 30.48 m h/d = 1.2

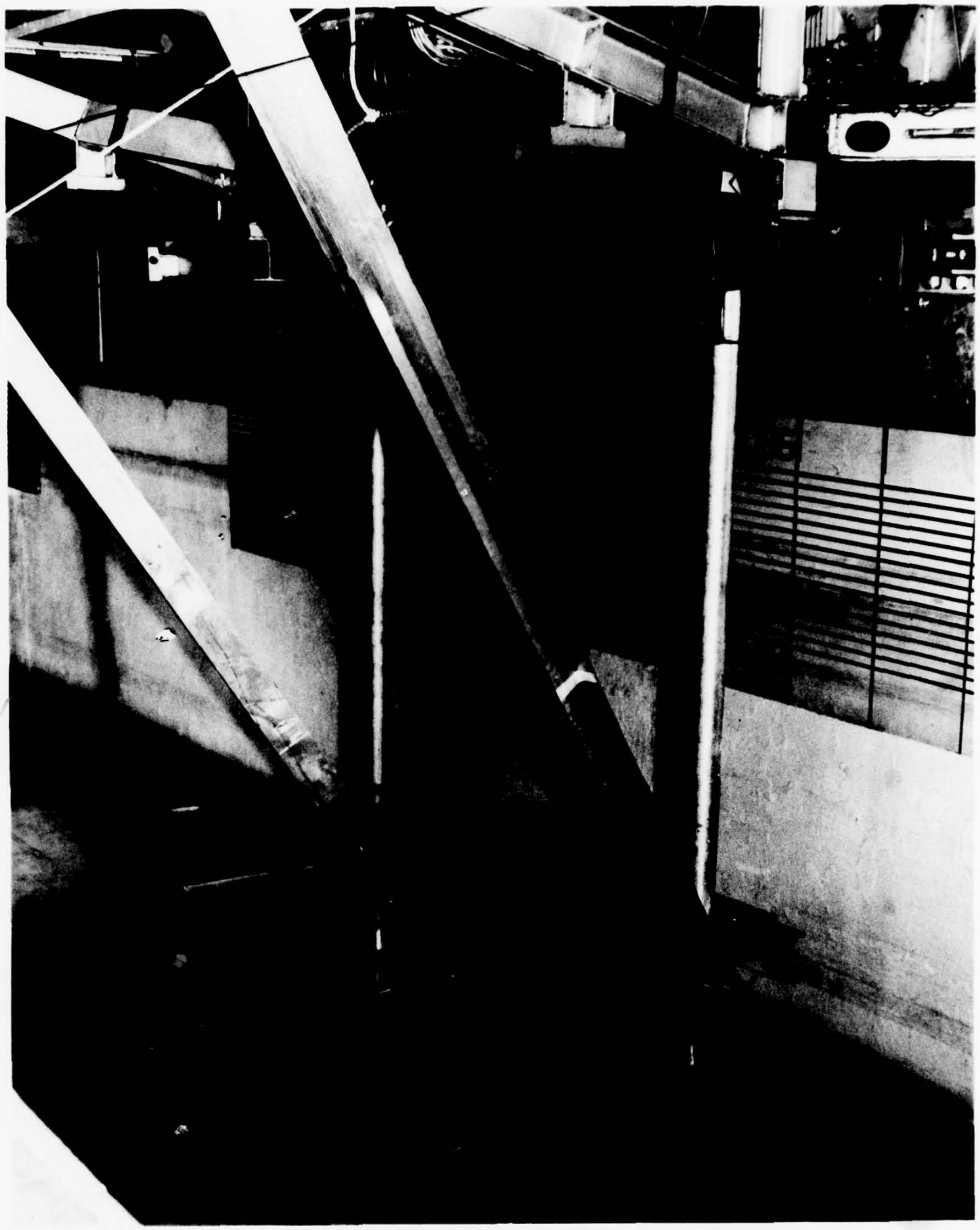


FIGURE 6   STRUT BRACING ARRANGEMENT ON THE CARRIAGE MODEL

FORCES AND MOMENTS DUE TO TWO SHIPS PASSING HEAD TO HEAD
IN A SHALLOW CHANNEL

model speed = **.55 m/s** (7.5 knots full scale)
h/d = 1.2
$\bar{\eta}$ = **.305 m** (**15.24 m** full scale)

POSITIVE SIDE FORCE = ATTRACTION
POSITIVE MOMENT = BOW ATTRACTION

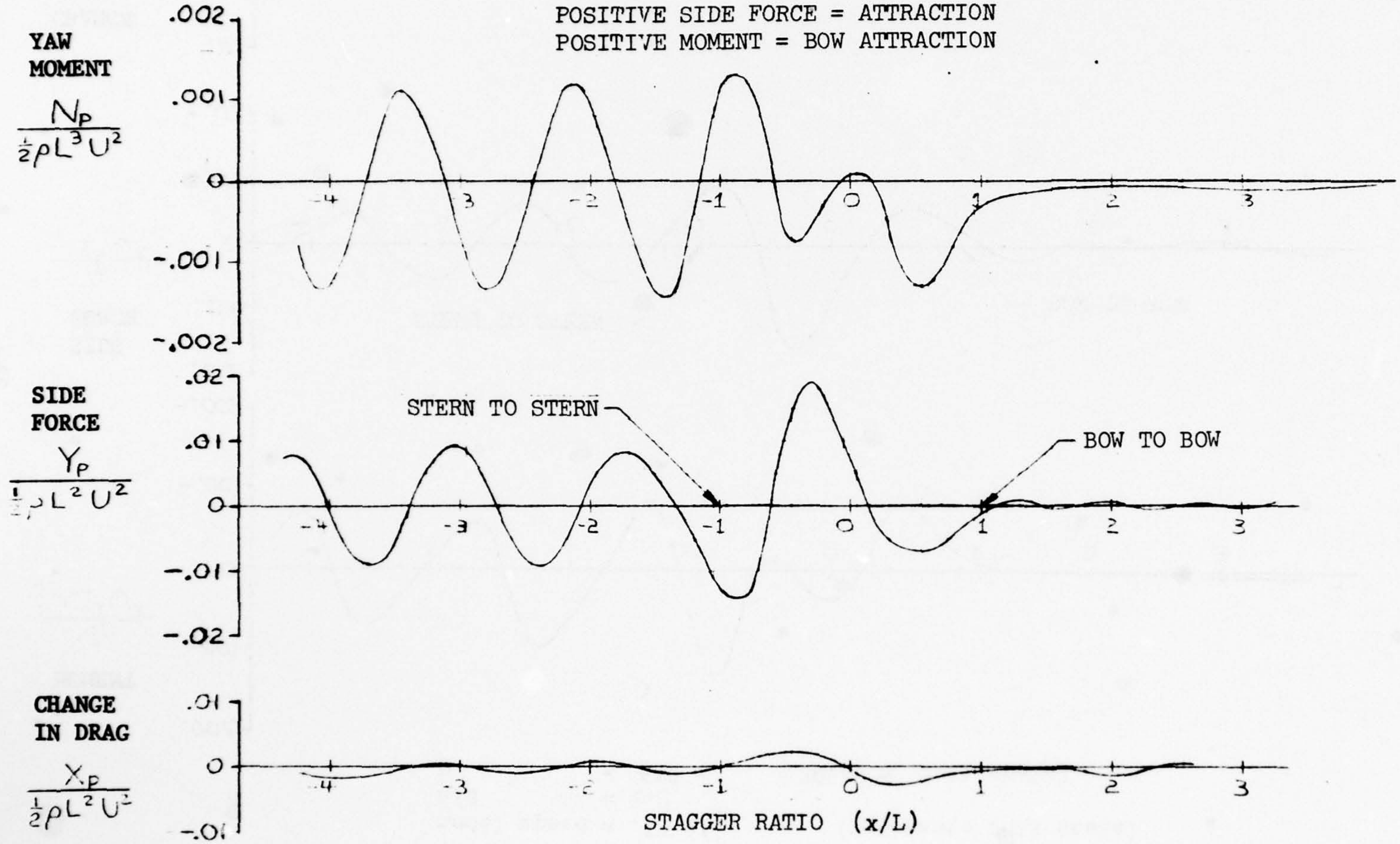


FIGURE 7

FORCES AND MOMENTS DUE TO TWO SHIPS PASSING HEAD TO HEAD
IN A SHALLOW CHANNEL

model speed = .55 m/s (7.5 knots full scale)
h/d = 1.2
$\bar{\eta}$ = .610 m (30.48 m full scale)

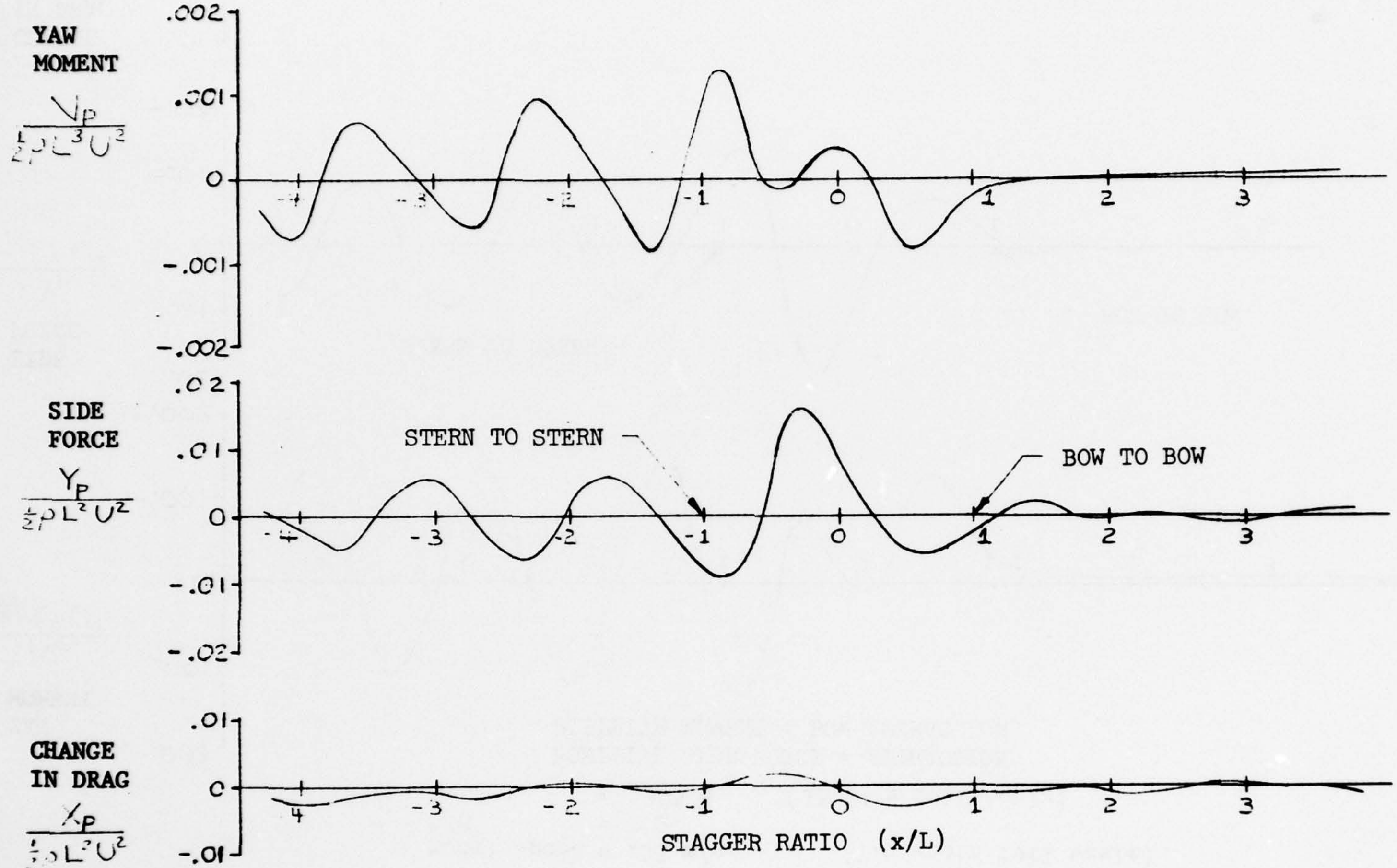


FIGURE 8

FORCES AND MOMENTS DUE TC TWO SHIPS PASSING HEAD TO HEAD
IN A SHALLOW CHANNEL

model speed = .55 m/s (7.5 knots full scale)
h/d = 1.5
$\bar{\eta}$ = .305 m (15.24 m full scale)

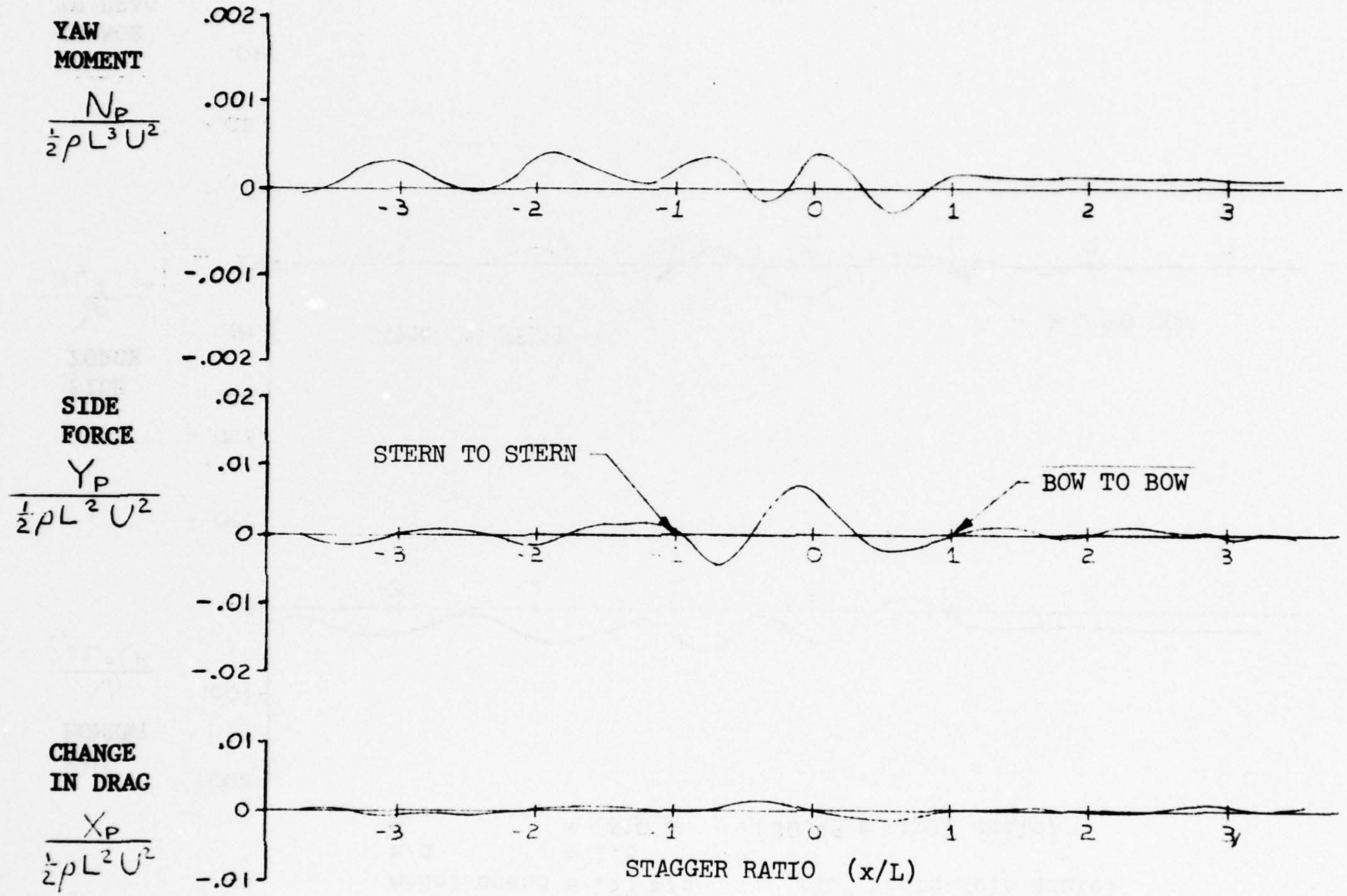


FIGURE 9

FORCES AND MOMENTS DUE TO TWO SHIPS PASSING HEAD TO HEAD IN A SHALLOW CHANNEL

model speed = **.55 m/s** (7.5 knots full scale)
h/d = 1.5
$\bar{\eta}$ = **.610 m** (**30.48 m** full scale)

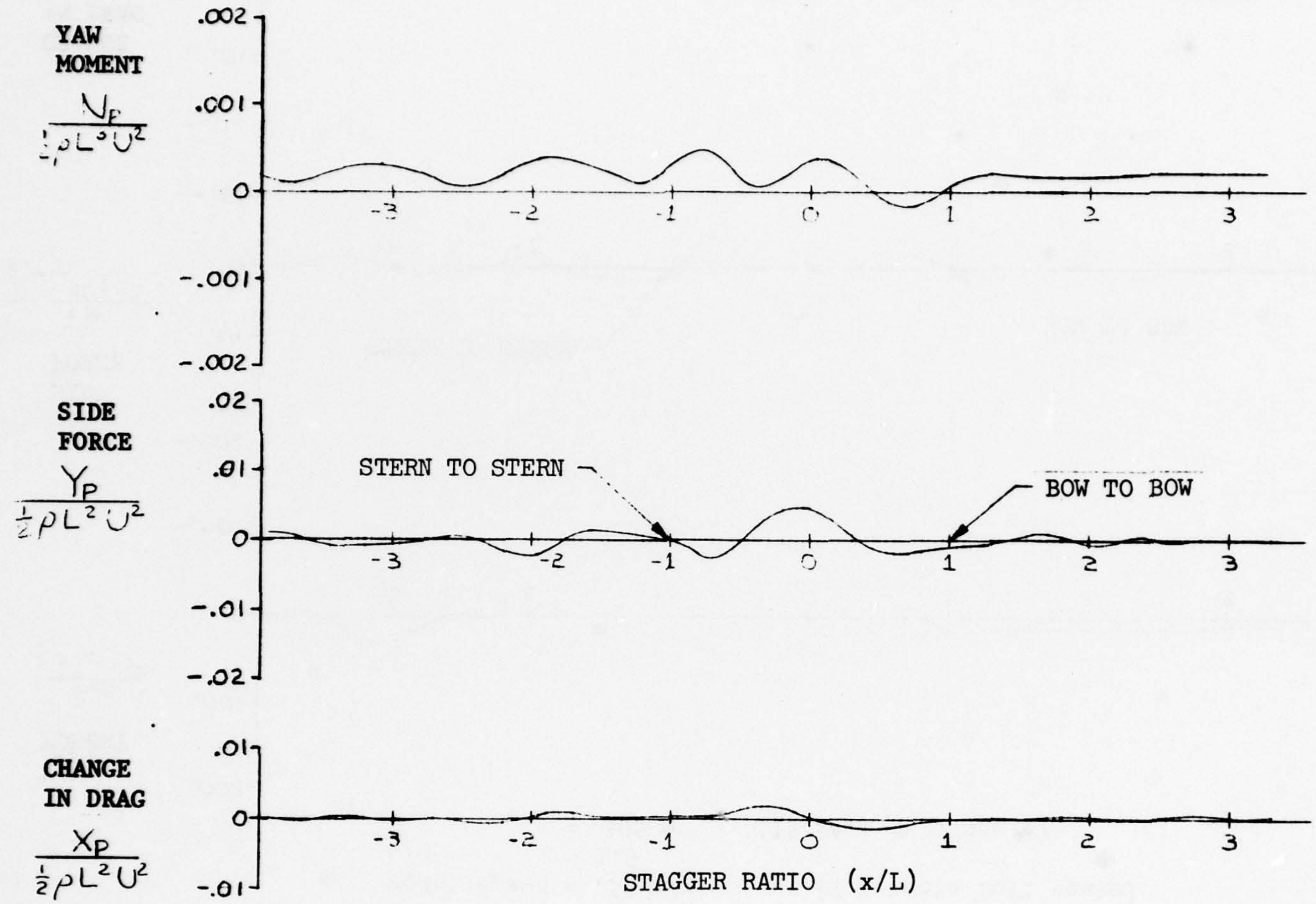


FIGURE 10

FORCES AND MOMENTS DUE TO TWO SHIPS PASSING HEAD TO HEAD IN A SHALLOW CHANNEL

model speed = .44 m/s (6.0 knots full scale)
h/d = 1.2
$\bar{\eta}$ = .305 m (15.24 m full scale)

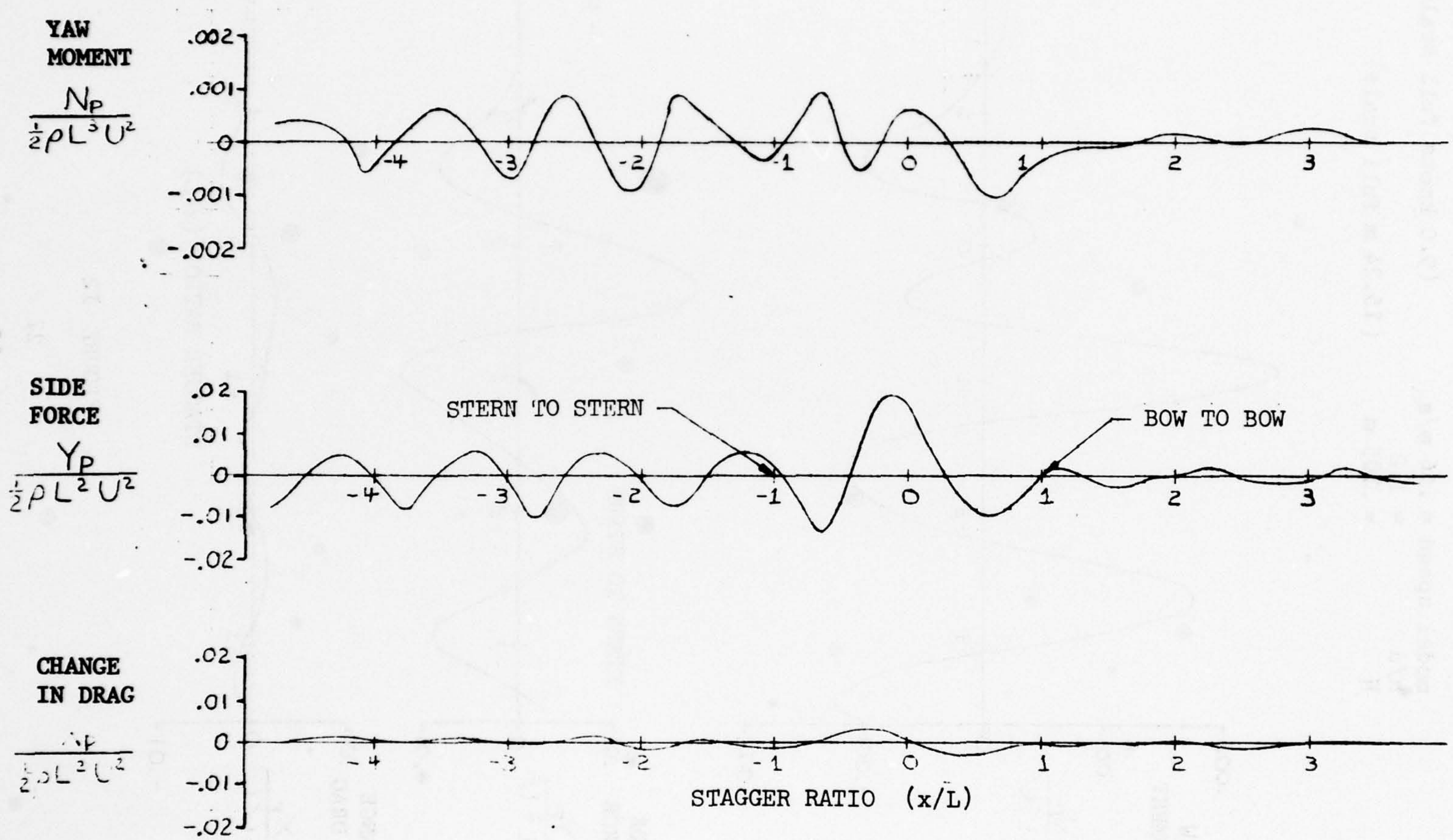


FIGURE 11

FORCES AND MOMENTS DUE TO TWO SHIPS PASSING HEAD TO HEAD
IN A SHALLOW CHANNEL

model speed = **.66 m/s** (9.0 knots full scale)
h/d = 1.2
$\bar{\eta}$ = **.305 m** (**15.24 m** full scale)

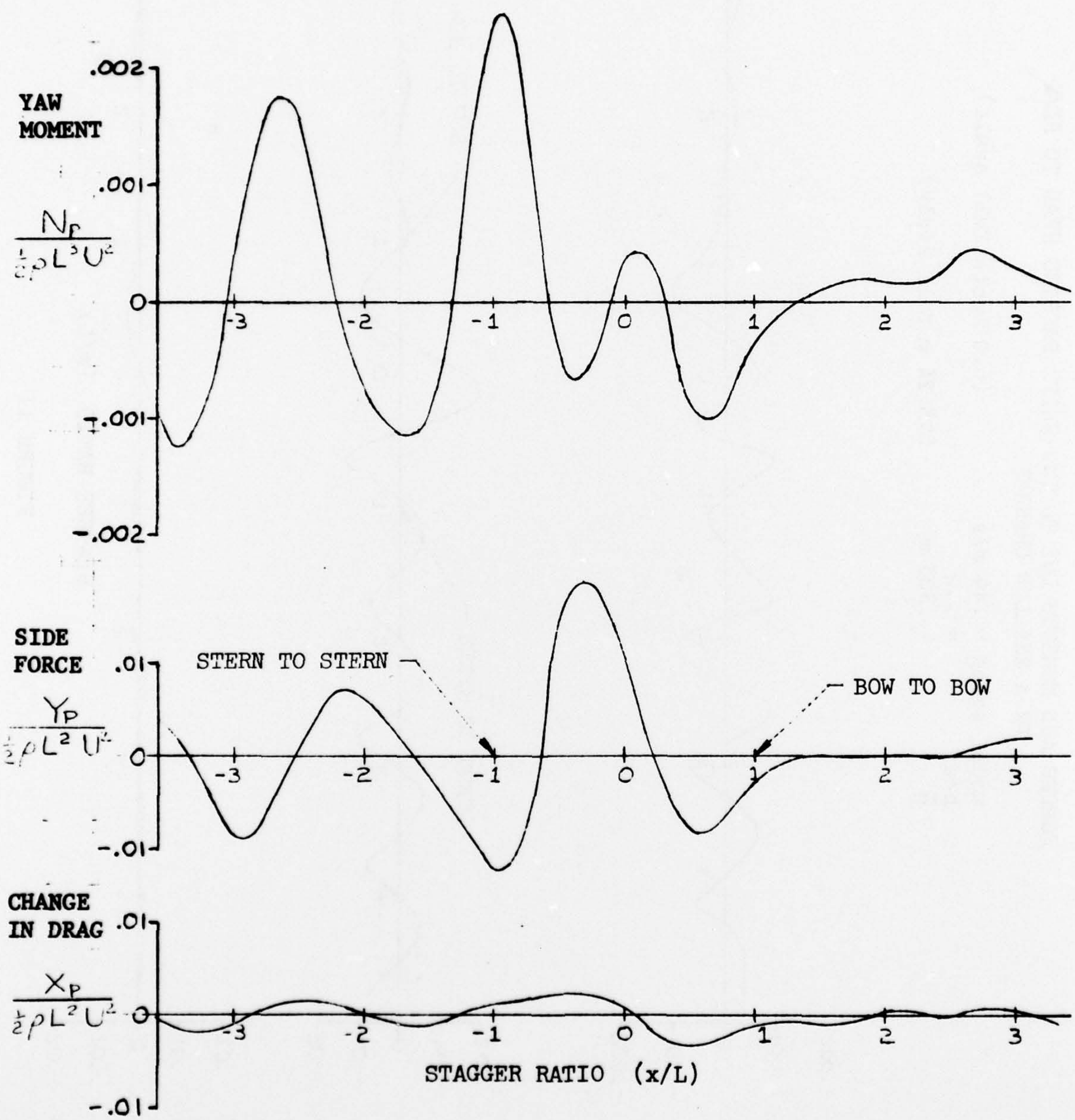


FIGURE 12

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

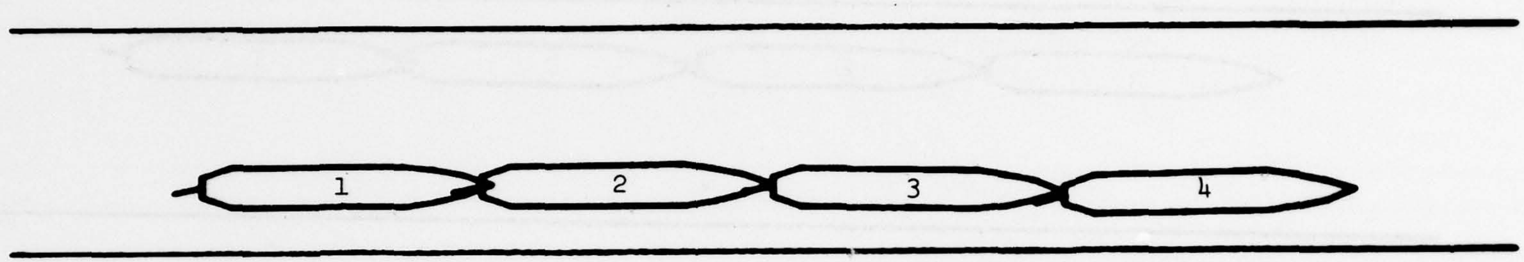


FIGURE 13 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 7.5 knots   h/d = 1.2 $\bar{\eta}_s$ = 15.24 m

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

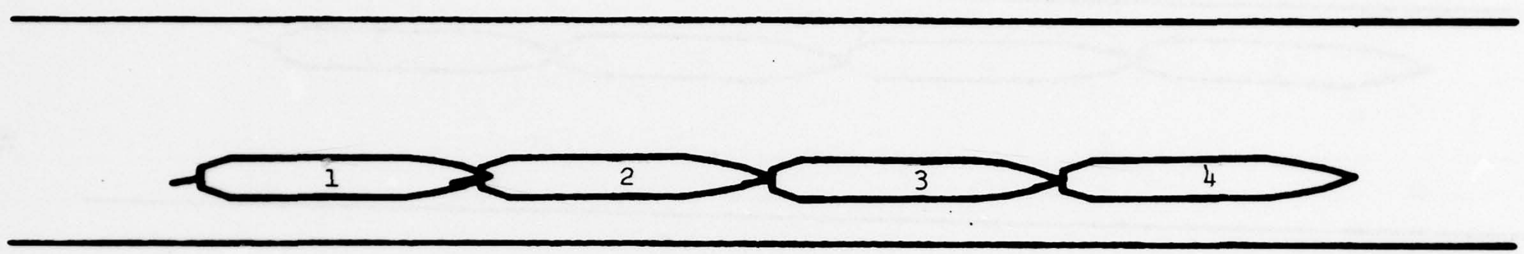


FIGURE 14 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 7.5 knots   h/d = 1.2 $\overline{\eta}_s$ = **30.48 m**

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

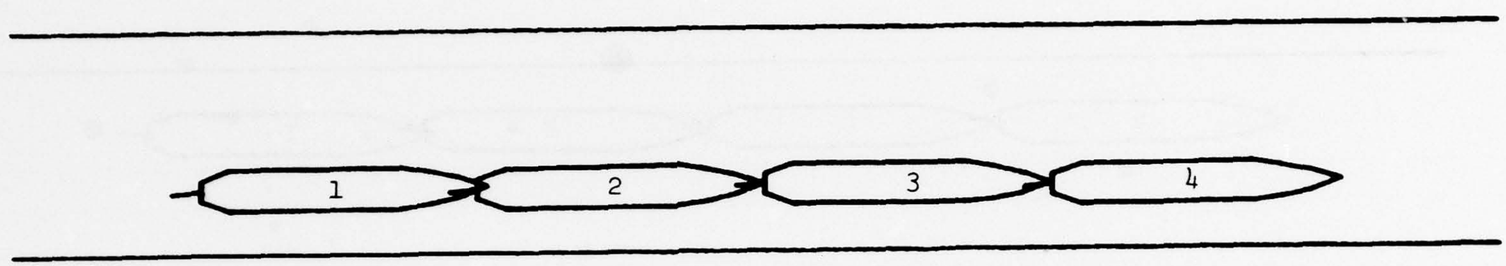


FIGURE 15 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 7.5 knots $\quad$ h/d = 1.5 $\quad$ $\bar{\eta}_s$ = 15.24 m

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

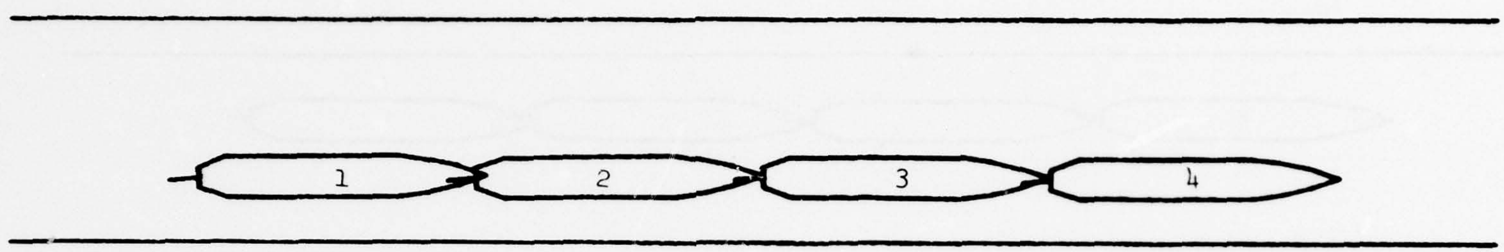


FIGURE 16 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 7.5 knots   h/d = 1.5 $\bar{\eta}_s$ = 30.48 m

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

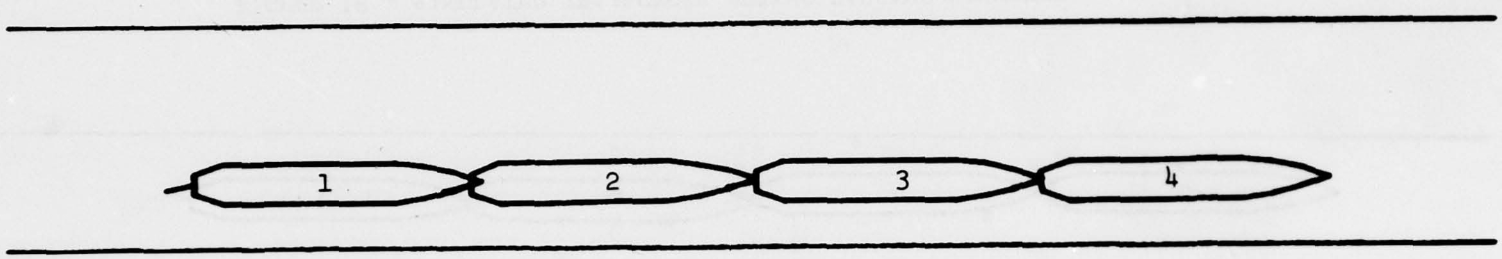


FIGURE 17 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 6.0 knots   h/d = 1.2 $\overline{\eta}_s$ = 15.24 m

POSITION	x/L	
1	3	
2	1	(bow to bow)
3	-1	(stern to stern)
4	-3	

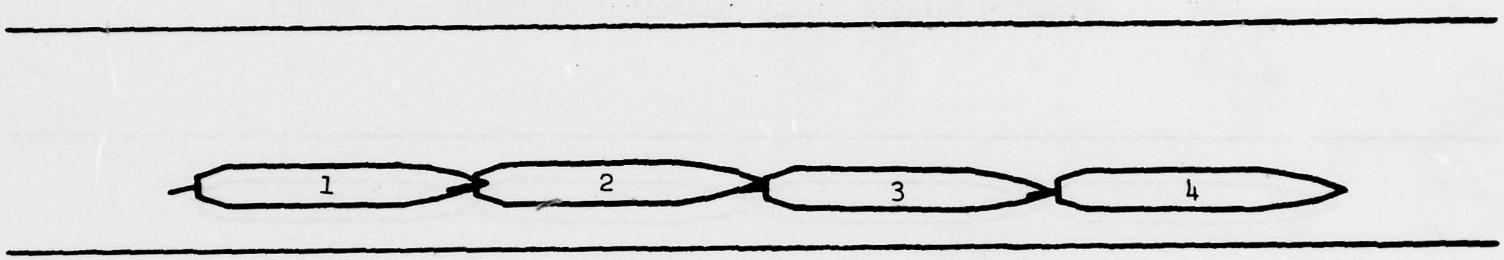


FIGURE 18 - SIMULATED TRAJECTORY DURING PASSING MANEUVER

U_s = 9.0 knots   h/d = 1.2 $\overline{\eta}_s$ = 15.24 m

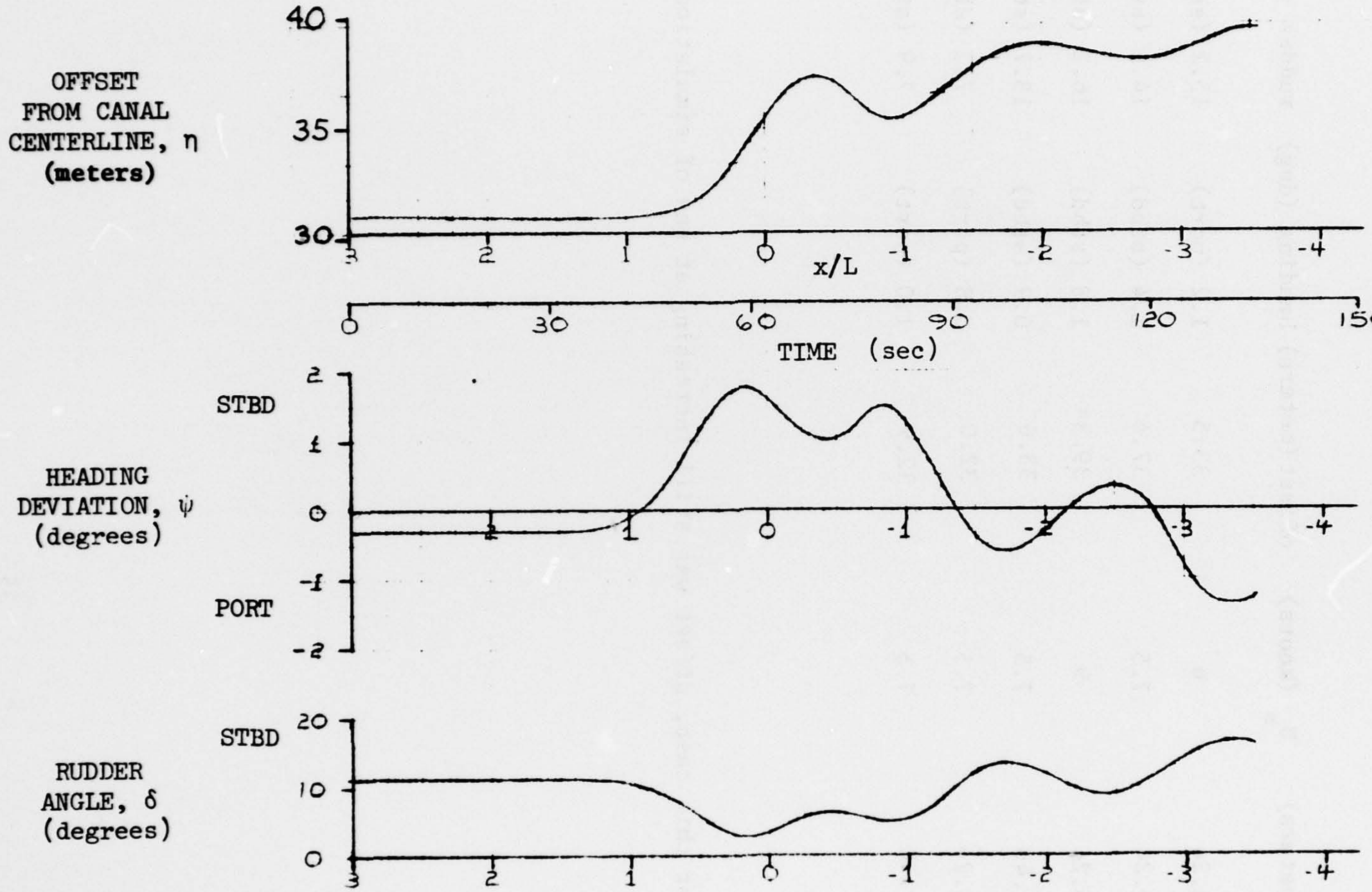


FIGURE 19 TIME HISTORY OF RUDDER ANGLE, HEADING, AND OFFSET FROM CENTERLINE OF CANAL

U_s = 9.0 knots h/d = 1.2 $\bar{\eta}_s$ = 15.24 m

TABLE 1

MAXIMUM VALUES OF LATERAL OFFSET, HEADING AND RUDDER ANGLE FOR SIMULATED PASSING MANEUVERS

h/d	$\bar{\eta}$ (meters)	U_s (knots)	offset (meters)	heading (deg)	rudder (deg)
1.2	15.24	6	33.5	1.2 (port)	15.2 (stbd)
1.2	15.24	7.5	37.4	1.4 (stbd)	14.6 (stbd)
1.2	15.24	9	39.3*	1.8 (stbd)	16.1 (stbd)
1.2	30.48	7.5	33.6	0.9 (stbd)	13.7 (stbd)
1.5	15.24	7.5	32.0	0.8 (port)	7.3 (stbd)
1.5	30.48	7.5	32.9	1.0 (port)	7.9 (stbd)

*Note: For this case, offset was still increasing at end of simulation

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